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Report

Motion Silences Awareness of Visual Change

Jordan W. Suchow[1,*] and George A. Alvarez[1]
[1]Department of Psychology, Harvard University, Cambridge, MA 02138, USA

Summary

Loud bangs, bright flashes, and intense shocks capture attention, but other changes—even those of similar magnitude—can go unnoticed. Demonstrations of change blindness have shown that observers fail to detect substantial alterations to a scene when distracted by an irrelevant flash, or when the alterations happen gradually [1–5]. Here, we show that objects changing in hue, luminance, size, or shape appear to stop changing when they move. This motion-induced failure to detect change, silencing, persists even though the observer attends to the objects, knows that they are changing, and can make veridical judgments about their current state. Silencing demonstrates the tight coupling of motion and object appearance.

Results

We created a series of movies in which 100 dots were arranged in a ring around a central fixation mark (Figure 1A). Each movie alternated between two phases, stationary and moving. During the stationary phase, the dots changed rapidly in hue, luminance, size, or shape. During the moving phase, the dots continued to change at the same rate while the entire ring rotated about its center. Observers were instructed to adjust the rate of change during the stationary phase to match the apparent rate of change in the moving phase. The results revealed a graded effect: the faster the ring rotated, the slower the dots seemed to change (Figure 1B). The fastest rotation (0.33 Hz) produced nearly complete silencing. Several visual demonstrations can be found at http://visionlab.harvard.edu/silencing/ and in the Supplemental Information available online (Movie S1, Movie S2, Movie S3, and Movie S4).

Determining the Perceived State

During silencing, rapidly changing objects appear nearly static, which raises an immediate question: What is the perceived state (e.g., red, bright, big, round) at any given moment? To illustrate, consider an observer who fails to notice an object change gradually from yellow to red. One possibility is that the observer always sees yellow, never updating his percept to incorporate the new hue—this is freezing, erroneously keeping hold of an outdated state [6]. Another possibility is that he always sees the current hue (e.g., yellow, orange, then red) but is unaware of the transition from one to the next—this is implicit updating [4].

Both accounts are plausible. Temporal freezing, filling-in, and illusory color-shape conjunction are three known phenomena in which the visual system paints a percept that differs from reality, either by retaining an outdated version of a changing stimulus or by inferring its current or future state [6–8]. Alternatively, in continuous change-blindness, part of a scene changes gradually, and though oblivious to the change, the observer perceives its current state veridically [3, 4].

To distinguish these two accounts of silencing—freezing and implicit updating—we created a change-detection task that generalizes Hollingworth and Henderson's reversion test [4]. In that study, observers viewed a picture of a room while, unbeknownst to them, the camera angle gradually shifted. After some time, the camera angle suddenly reverted to its original state. Observers pressed a button if they saw the picture change. The two accounts make different predictions as to whether the observers noticed the reversion: implicit updating predicts success, whereas freezing predicts failure. In fact, the reversion was obvious, ruling against freezing and in favor of implicit updating [4]. Here, instead of performing a single test in which the dots flip to their original state (i.e., their hue at the onset of motion), we performed a separate test for each state in the dots' history—past, present, and future. This generalized reversion test affords greater sensitivity in determining the perceived state. The two accounts both predict that observers will notice some reversions while failing to notice others but differ as to which reversions they predict will go unnoticed (Figure 2; red segments in "predictions" panel at top).

We found that observers noticed flips to the past and future, but not to the present (Figure 2; bottom panel); this occurred regardless of whether the objects stopped, continued to move, or were masked at the time of the reversion. The average magnitude of an unnoticed flip was $-14^\circ \pm 12^\circ$ (mean ± standard error of the mean [SEM]) when the objects stopped moving, $-8^\circ \pm 10^\circ$ when they continued, and $-14^\circ \pm 11^\circ$ when they were masked. Though each of these values is slightly negative, none are significantly different from 0° (one-sample test for mean angle of circular data, $p = 0.23$, $p = 0.43$, and $p = 0.20$, respectively), and all are reliably different from 180° ($p < 0.001$ for each). Importantly, each distribution is markedly nonuniform, which implies that observers were able to make a judgment that depended on the objects' state (Rayleigh test for uniformity of circular data, $p < 0.001$ for each). Silenced changes are updated implicitly—the observer sees the current state.

Incidentally, freezing of stationary color changes has been found to last for ≈200 ms [6], which corresponds to a -10° change in hue in our reversion test. Though the data rule out the possibility that temporal freezing explains silencing, they leave open the possibility that freezing persists within a local window, such that the perceived color consistently lags a bit behind the actual color; this would explain the observed, though not statistically significant, lag.

Motion in Space versus on the Retina

When an object moves but the observer's gaze does not—as in the movies presented here—two types of motion occur simultaneously: the object moves in space, and its image moves on the retina. Which causes silencing? We created four variants of the original movie that together dissociate the two types of motion. In the first variant, the object moves while the observer's gaze remains fixed, producing motion both in space and on the retina. In the second, the object moves

*Correspondence: suchow@fas.harvard.edu

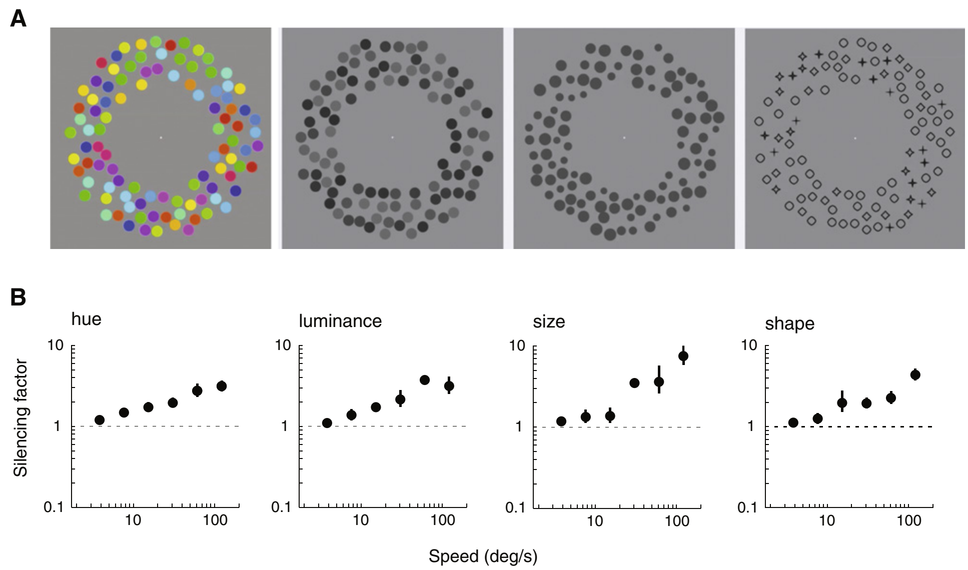

Figure 1. Motion Silences Awareness of Changes in Hue, Luminance, Size, and Shape

(A) One hundred dots are arranged in a ring around a central fixation mark. During the experiment, each dot changes rapidly in (left to right) hue, luminance, size, or shape. When the ring is briskly rotated about its center, the dots appear to stop changing—this is silencing. See also Movie S1, Movie S2, Movie S3, and Movie S4.

(B) The more rapid the rotation, the stronger the silencing. Its strength can be expressed as a silencing factor, the ratio of the actual to perceived rate of change as determined by a matching task (see experiment 1 in Experimental Procedures). The dashed line delineates veridicality (a silencing factor of 1), and points above the line show silencing. Error bars denote the within-subject standard error of the mean.

and the eyes follow, producing motion in space but not on the retina. In the third, the eyes move while the object remains fixed, producing motion on the retina but not in space. In the fourth, neither the object nor the eyes move.

Comparison across the four variants revealed that motion on the retina is responsible for silencing (Figure 3A). The strength of silencing can be expressed as a silencing factor, the ratio of the actual to perceived rate of change. Like in the previous experiment, motion both in space and on the retina produced strong silencing, 5 ± 1 (mean ± SEM). Critically, motion only on the retina also produced strong silencing, 4.3 ± 0.2, whereas motion only in space produced weak silencing, 1.4 ± 0.2. Of course, in the absence of motion, no silencing was observed (1.03 ± 0.04, not significantly different from 1, $p = 0.50$).

The mild silencing (1.4) found here for motion in space is a byproduct of faulty fixation. Note that to isolate motion in space, we asked observers to track a fast-moving fixation mark that traveled with the moving objects. Any failure on the part of the observer to accurately track the fixation mark would produce unwanted retinal motion, conflating the two. A signature of such unwanted retinal motion is a tight correlation between observers' success in tracking the fixation mark and the amount of observed silencing. We asked observers to perform a separate fixation-tracking task (see "Fixation-Tracking Accuracy" in Experimental Procedures) and measured the correlation of their accuracy in tracking with the silencing factor that had seemingly been produced by motion in space. Not only was this correlation high ($r^2 = 0.92$, $p = 0.01$), extrapolating the line best fit (by linear least-squares regression) to log silencing factor versus error rate on the fixation task predicted a silencing factor of 0.93 for an observer who flawlessly tracked the fixation mark—no silencing (Figure 3B). Thus, motion on the retina is responsible for the full effect of silencing, whereas motion in space is irrelevant. The silencing factors reported above were calculated using data from JS and MP, two practiced psychophysical observers who had the two lowest error rates on the tracking task (0.13 and 0.25 errors per second, respectively).

Discussion

To detect that a moving object is changing, the visual system must track the object's state. Presumably, the mechanisms that carry out these measurements are local—i.e., each monitors a fixed location in the visual field that corresponds to a fixed location on the retina [9]. Because a fast-moving object spends little time at any one location, a local detector is afforded only a brief window in which to assess the changing object [10]. This brief exposure may be insufficient to detect any changes, or perhaps insufficient to properly attribute detected changes to anything other than motion (e.g., to change in hue or size). This proposed dependence of change detection on the success of local retinotopic detectors helps to explain why fast motion produces more silencing than slow motion and why motion on the retina produces more silencing than motion in space. Silencing provides a method to infer the receptive field size of these local change detectors, though such a calculation would depend critically on their shape and sensitivity.

Conceivably, the brief exposure afforded by a fast-moving object could be lengthened by rapidly shifting the focus of attention over a moving window [10, 11]. Here, tight spacing precluded isolation, and explicit instructions to pay attention to the whole set discouraged any shifts of attention. Manipulating the number of dots or asking observers to attend to only a few of them might reveal the role of attention in silencing.

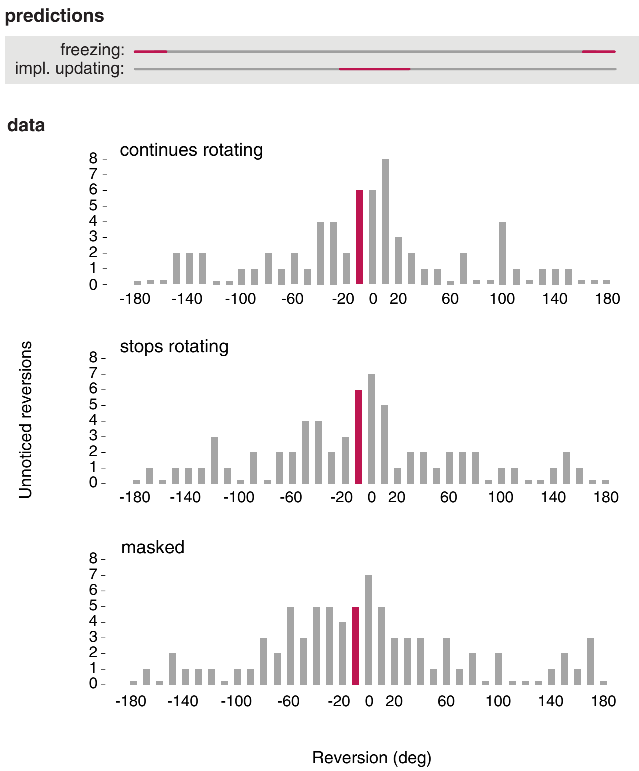

Figure 2. Distinguishing between Two Accounts of Silencing

Freezing or implicit updating? The two accounts make different predictions for the results of this change detection task, in which the dots' hue flips to a past, present, or future state and the observer is asked whether the hue changed. The horizontal axis gives the magnitude of the reversion: the leftmost point, −180°, corresponds to the hue at the onset of motion, whereas the central point, 0°, corresponds to the hue at the time of the flip. Freezing predicts that only large reversions (±180°) go unnoticed, whereas implicit updating predicts that only small reversions (0°) go unnoticed (see red segments in "predictions" panel at top). In the data, each red bar is the experimentally observed average unnoticed reversion. The results match the predictions of implicit updating, but not freezing.

Having failed to notice that any individual dot was changing, observers could still have detected a change to the set by combining information across dots to form a summary representation (e.g., by monitoring the average color or size) [12, 13]. We prevented this strategy by pairing a distribution of states (circular uniform) with a method of change (rotation) such that the set remained the same even while its elements rapidly changed. With no spared mechanism by which to detect change, silencing is revealed.

Motion and object-identity processing are fundamental to vision but are often studied independently and thought to occur in complementary processing streams [14]. Silencing demonstrates the tight coupling of motion and object appearance. Simply by changing the retinotopic coordinates—moving the object or the eyes—it is possible to silence awareness of visual change, causing objects that had once been obviously dynamic to suddenly appear static.

Experimental Procedures

Observers

Six observers participated in experiment 1, six in experiment 2, and eight in experiment 3. One of the observers in each experiment was author J.W.S.; the other observers were naive to the purpose of the experiment. All observers were between the ages of 20 and 35 and had normal or corrected-to-normal vision.

Presentation

Movies were rendered by an Apple Macintosh computer running MATLAB with the Psychophysics Toolbox [15, 16]. The display's resolution was 1280 × 800 at 60 Hz, and it had a pixel density of 113 ppi (44 pixels/cm). The viewing distance was 57 cm. The background was gray, with a luminance of 25 cd/m^2.

Experiment 1: Effect of Speed

One hundred dots were arranged in a ring with an inner radius of 5° of visual angle and an outer radius of 8°. Each dot was 1° in diameter and was positioned randomly in the ring, with the constraint that no two dots overlapped. Observers were instructed to pay attention to all of the dots. A small white fixation mark was placed in the center of the ring. On each trial, the ring was at first stationary and then rotated about its center, reversing direction each time it completed 30°. The two phases, stationary and moving, alternated every 3 s. All the while, the dots changed rapidly in hue, luminance, size, or shape. At the start of each trial, the rate of change during the two phases was identical, though they did not necessarily appear to match. Observers were asked to adjust the rate of change during the stationary phase to match the apparent rate of change in the moving phase by moving a mouse forward (faster) or backward (slower). Using this adjustment procedure, observers could produce a rate of change up to ten times faster or slower than the initial rate, thereby creating a silencing factor between 0.1 and 10. Observers performed three trials at each of six angular velocities: 3.75°, 7.5°, 15°, 30°, 60°, and 120° per second.

Changing Hue

Each dot was a brightly colored circle. There are many ways to describe color, and we used the HSV color space because it provides a convenient way to specify the rate of change. The HSV color space has three axes: hue, saturation, and value. Saturation and value were fixed at 100%, and the initial hue of each dot was chosen uniformly over the entire range, 0°–360°. The hue changed at a rate of 75° per second, clockwise.

Changing Luminance

Each dot was a gray circle that flickered sinusoidally at 1 Hz, with a mean amplitude of 15 cd/m^2.

Changing Shape

Each dot was a superellipse. A superellipse is a generalization of an ellipse that includes familiar shapes like circles, squares, and diamonds as well

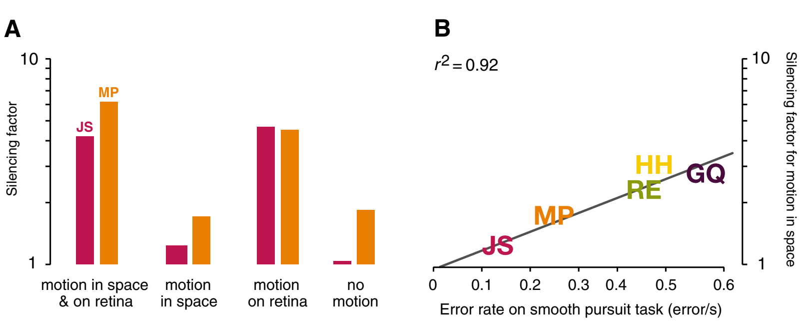

Figure 3. Is Silencing Caused by Motion in Space or Motion on the Retina?

(A) Motion on the retina produces as much silencing alone as when combined with motion in space. These data are from two observers, JS (red) and MP (orange).

(B) The mild silencing that is seemingly produced by motion in space is nothing but a byproduct of faulty fixation—i.e., observers who show less error in tracking the fixation mark also show less silencing (r^2 = 0.92, p = 0.01). Points are labeled with the observers' initials. Extrapolating the best-fit line confirms that motion on the retina, not in space, causes silencing.

as unfamiliar shapes like squircles and squashed astroids [17–20] (see Figure S1). It is defined by the set of all points (x, y) such that

$$\left|\frac{x}{a}\right|^r + \left|\frac{y}{b}\right|^r = 1$$

where a is the length of the semimajor axis, b is the length of the semiminor axis, and r is a positive real number that determines the shape's bulge. We set $a = b = 0.75^\circ$ of visual angle and transformed each dot by linearly ramping r from 0 to 2 and back—this is one cycle. We define the rate of shape change as the frequency of the ramping, here 1 Hz. This particular choice of shape morph is arbitrary, but the underlying principle—selecting a parameterized family of shapes and creating morphs by ramping each parameter in a specified way—provides a wholly reproducible method for exploring the effects of different shape transformations.

Changing Size

Each dot was a dark gray (10 cd/m^2) circle whose diameter varied sinusoidally at 1 Hz, with a mean amplitude of 1° of visual angle.

Experiment 2: Motion in Space versus on the Retina

One hundred dots were placed uniformly on the display. Each dot was 1° of visual angle in diameter and changed hue at 120° per second. Two fixation marks were placed at the center of the screen. If the dots moved, each traveled rightward at 10° per second and was replaced at the left edge of the screen when it hit the right. No matter the condition, one of the fixation marks traveled rightward at 10° per second (and was also replaced at the left edge when it hit the right) while the other stayed in place. The procedure was the same as in experiment 1, except that, when appropriate, observers were instructed to track the moving fixation mark while performing the adjustment task. Observers performed three trials in each of four conditions: objects and eyes move, objects move, eyes move, neither move.

Fixation-Tracking Accuracy

We created a variant of Guzman-Martinez et al.'s fixation task, in which observers view a patch of binary noise that flickers rapidly in counterphase (i.e., each pixel alternates between white and black) [21]. When the eyes are still, the patch appears uniformly gray. If the eyes move with respect to the patch, then it appears to flicker once. In our variant, the fixation mark and accompanying noise patch moved together across the screen. Observers tracked the fixation mark with their eyes and pressed a button whenever the patch flickered. Each reported flicker was scored as a tracking error. Observers were not informed that the flickering was caused by their eye movements. The trial lasted 120 s.

Experiment 3: Freezing versus Implicit Updating

The movies used here were identical to those used in experiment 1, except that the ring rotated 180° in one direction, once. The speed of rotation and rate of hue change were matched at 75° per second such that, over the course of the 180° rotation, each dot also completed a 180° change in hue. After the rotation, the dots reverted, together shifting in hue by an amount drawn uniformly over -180° and 180°. In one condition, the reverted ring continued to rotate until a response was made. In a second condition, the ring remained still after the reversion. In a third condition, the first 100 ms following the reversion contained a mask. The mask was a colorful noise pattern with 2×2 pixel square checks, each filled with a color drawn independently from the same color space as the dots. Trials were blocked by condition. After the display had rotated 180°, the fixation mark changed from white to black, announcing the reversion. Observers were asked whether the objects in the ring changed color when the fixation mark changed and responded "change" or "no change" by pressing a button. Observers performed one trial for each of 36 reversions, -180°, -170°, …, 170°, ordered randomly.

Supplemental Information

Supplemental Information includes one figure and four movies and can be found with this article online at doi:10.1016/j.cub.2010.12.019.

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